# A Gaussian Plume-based Population Exposure Approach to Railroad Transportation of Hazardous Materials

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***Abstract* –Hazardous materials (hazmat) are potentially harmful to people and environment due to their toxic ingredients. Although a significant portion of hazmat is transported via rail-roads, until recently the focus was on highway shipments. In this work, we develop a risk assessment methodology that takes into consideration the differentiating features of trains and the characteristics of train accident. The proposed methodology, which includes Bayes theorem and logical diagrams, was used to study a US based case example, which was further analyzed to gain relevant managerial insights.**

***Index Terms* –risk assessment, railroad transport, air dispersion models, dangerous goods.**

## I. Introduction

Hazardous materials (hazmat) are harmful to humans and the environment because of their toxic ingredients, but their transportation is essential to sustain our industrial lifestyle. A significant majority of hazmat shipments are moved via the highway and railroad networks. For example, in Canada, around 29 million tons are moved by railroads [1], whereas the equivalent number is 130 million tons for the United States [2]. The quantity of hazmat traffic on railroad networks is expected to increase significantly over the next decade, due in part to the phenomenal growth of intermodal transportation and the growing use of rail-truck combination to move chemicals. In spite of the favorable safety statistic of railroads [3], the possibility of spectacular events resulting from multi railcar incidents, however small, does exist. For example, in the United States, between 1995 and 2009, around 120 train accidents resulted in release from multiple railcars, which translates into an average of eight accidents per year [2].

It was interesting to note that despite the quantity of hazmat moved by rail, an overwhelming majority of research on hazmat transportation focuses on road shipments [4]. The sparse literature of railroad transportation of hazmat mainly deals with analyzing past accident data in an effort to increase railroad safety by improving rail-tracks or railcar tank designs. We invite the reader to refer to [5] for a state of art review of the work done in this domain. This paper proposes a risk assessment methodology that takes into consideration: (a) the probability that a train carrying hazmat will be involved in an accident; (b) the conditional probability that a hazmat railcar will derail; (c) the conditional probability that the railcar will rupture and release its contents; and, (d) the consequence as a result of hazmat release from multiple sources.In an effort to get an insight into the causes and related characteristics of railroad accidents, we collected information on freight derailment from the Federal Railroad Administration (FRA) database [6]. It is important to note that the 25,000 derailment instances could have been further processed to reveal position-specific derailment probabilities, but such numbers do not have much use since freight-train lengths vary. Hence, we propose a *decile* based approach, where the train length is divided into ten equal parts. In addition, consistent with literature [7], we assume that trains can be categorized based on lengths into: *short* (less than 40 railcars); *medium* (40 to 120 railcars); and *long*. Based on this categorization, of the 25K accident instances in our database, 93% resulted from freight-train with less than 121 railcars, wherein *medium* trains accounted for 56%.

The remainder of the paper is organized as follows. In §2 we outline the proposed risk assessment methodology, followed by its application to a realistic size problem instance in §3, and finally conclusion in §4.

## II. Risk Assessment Framework

We make use of the expected consequence approach, defined as the *probability* of accident times the resulting *consequence*, to measure transport risk. This measure, also called the traditional risk, has been used to evaluate hazmat transport risk of highway shipments and requires estimating the two parameters [8].

### A. Rail-Link Risk

Consider a rail-link $l$ of unit length. If the probability that a train meets with an accident on this rail-link is given by $P(A_l)$ and the resulting consequence by $C(A_l)$, then the risk posed by the transportation of hazmat over $l$ can be represented by:

$$Risk_l = P(A_l) \times C(A_l) \tag{1}$$

where $C(A_l)$ would be determined as:

$$C(A_l) = P(D^i \mid A_l) \times P(H \mid D^i, A_l) \times P(R \mid H, D^i, A_l) \times PE_l \tag{2}$$

where, $P(D^i \mid A_l)$ = probability of derailment of a railcar in the $i^{th}$ decile of the train given the accident on link $l$;




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$P(H \mid D^i, A_l) =$ probability that a hazmat railcar derailed in the $i^{th}$ decile of the train given the accident on link $l$; $P(R \mid H, D^i, A_l) =$ probability of release from a hazmat railcar derailed in the $i^{th}$ decile of the train given the accident on link $l$; and, $PE_l =$ population exposure due to the release from hazmat railcars given the accident on link $l$. While eqn. (1) is the well-known definition of traditional risk, eqn. (2) is the adaptation necessary to incorporate the characteristics of railroad accidents.

Note that it is impossible to conduct a comprehensive risk assessment since the impact of most hazmat on human life and their interactions are unknown. The most elaborate study considered just the top 102 hazardous commodities moved by tank cars to generate 5,151 binary combinations of which 1,210 were deemed incompatible [9]. This is important since railroads generally transport multiple hazmat, and proper risk assessment would require development of an approximation technique. To tide over the dearth of work on hazmat incompatibility and interactions, we propose adopting a conservative approach by basing evaluation on the hazmat likely to be most detrimental. Such an approach is desirable for three reasons: *first*, it will preclude underestimation of risk; *second*, it will facilitate better emergency response preparedness since the hazmat being considered is likely to cause maximum damage; and *third*, it will offset the adverse impact of not keeping track of individual hazmat.

*Population Exposure:* The population exposure approach, as proposed in [10] and [11], is modified to incorporate the possibility and volume of hazmat released from multiple sources. This dependence relationship can be represented by (3).

$$PE_l = f(V_l, \rho(V_l)) \quad (3)$$

where, $V_l =$ volume of hazmat released due to the accident on rail-link $l$; and, $\rho(V_l) =$ population density of centers exposed due to $V_l$. Since complete information on hazmat interaction is not known, we make use of the approximate methodology outlined earlier and work with total volume of hazmat released from all sources. It is important to note that approximate assessment is required only when there is no information on the interaction effects of the hazmat in question, and should be replaced with exact assessment when such information is available. If $v_l^n$ is the quantity of hazmat released from railcar $n$ due to the accident on link $l$, the total volume of hazmat released from all the sources due to the accident on link $l$, can be determined by:

$$V_l = \sum_n v_l^n \quad (4)$$

For *a priori* risk assessment, we propose loss of entire lading from a tank car (or railcar) when no information on volume is available. This assumption is reasonable and was arrived at after simulating a number of release scenarios in ALOHA, an atmospheric dispersion model used for evaluating release of hazardous chemicals [12]. If the impact area is represented as a danger-circle (of radius $\hat{X}$), then the hazmat transport activity can be visualized as the movement of this circle along the rail-link (of length $l$), which carves out a band as the region of possible impacts (fig.1). The number of people living in the band is the *population exposure* [9].

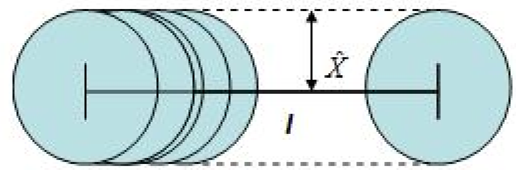


Fig. 1. Exposure zone

Evacuation Distance: We focus on hazmat that become airborne on release (such as chlorine, propane and ammonia), since they can travel long distances and expose large areas to health and environmental risks. The spatial distribution of the toxic concentration level, stemming from such release, can be (approximately) estimated through air dispersion models, and we select the most popular one viz. Gaussian plume model (GPM). We make use of the observation that downwind locations receive maximum concentration for any given distance, and hazmat specific immediately dangerous to life and health (IDLH) levels in determining the evacuation distance [13].

The standard GPM, appropriate for representing a single release source, is first adapted and then extended to model train shipments, which may involve multiple release-sources [12]. At zero elevation of both the release source and the impact point, and for downwind points, the single railcar release source can be modeled as:

$$C(x) = \frac{Q}{\pi\, u\, \sigma_y\, \sigma_z} \quad (5)$$

where $C(x)$ is the concentration level (ppm) at downwind point $(x)$ in steady-state; $Q$ is the release rate of pollutant (mg/s); $u$ is the average wind-speed (m/s); $\sigma_y$ the horizontal dispersion coefficient (m), $\sigma_y = ax^b$; $\sigma_z$ the vertical dispersion coefficient (m), $\sigma_z = cx^d$; and, $x$ the downwind distance from the source (m). In estimating the steady-state concentration level at point *(x)*, the model assumes that the release rate and atmospheric conditions remain constant over the period of dispersion.

We make use of observation that pollution from an array of sources, with an arbitrary distribution of position and strength of emission, can be modeled by superimposing patterns of pollution from multiple sources of release [14]. Furthermore, we make use of an approximation methodology available in literature and presume that all the sources of release are positioned at the hazmat-median (i.e., center of the hazmat block) of the train [12]. After incorporating these two attributes, aggregate release from multiple sources can



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be determined by :

$$\overline{C}_n(x) = \frac{\sum_{i=1}^{n} n_i Q_i}{\pi\, u\, a\, c\, x^b x^d} \tag{6}$$

where $\overline{C}_n(x)$ is the aggregate concentrate level at downwind distance $x$ due to hazmat released from $n$ different railcars; and, $n_i$ is the number of hazmat railcars with a release rate of $Q_i$ . Other parameters are as before. If the *IDLH* concentrate level of the hazmat being transported is $\tilde{C}$ , (6) can be re-arranged to arrive at the expression for determining evacuation distance:

$$\tilde{X} = \sqrt[b+d]{\frac{\sum_{i=1}^{n} n_i Q_i}{\pi\, u\, a\, c\, \tilde{C}}} \tag{7}$$

It should be clear that (7) aggregates contaminants from multiple sources of release, and thus also captures volume of hazmat released. The evacuation distance, $\hat{X}$ , determines the population centers likely to be exposed due to the train accident on link *l*, which will be used to calculate the corresponding population exposure.

### *B. Rail-Route Risk*

Having outlined the estimation technique for rail-link above, we now present the approach needed for rail-route.For railroads, a route is a collection of rail-links and intermediate yards connecting the origin and destination for the specific freight-train. If the route is comprised of rail-links *l* and *l+1*, then it is easy to see that travel on this route is a probabilistic experiment, since the expected consequence on rail-link *l+1* is dependent on whether the train meets with an accident on link *l*. One can determine the expected consequence associated with this route by:

$$P(A_l)C(A_l) + [1 - P(A_l)]\, P(A_{l+1})C(A_{l+1}) \tag{8}$$

where, $P(A_{l+1})$ is the probability of meeting with an accident on link *l+1*, and $C(A_{l+1})$ is the resulting consequence. To generalize, if there are *m* rail-links in the route under consideration, the expected consequence associated with this route would be expressed as follows:

$$P(A_l)C(A_l) + [1 - P(A_l)]\, P(A_{l+1})C(A_{l+1}) + ..$$
$$.......... + \left\{ \prod_{i=l}^{m-1} [1 - P(A_i)] \right\} P(A_m)C(A_m) \tag{9}$$

where, the expected consequence of the $k^{th}$ rail-link is $[1 - P(A_1)][1 - P(A_2)].......[1 - P(A_{k-1})]P(A_k)C(A_k)$ .

## III. Problem Instance

### *A. Experimental Setting*

The assessment methodology developed in the previous

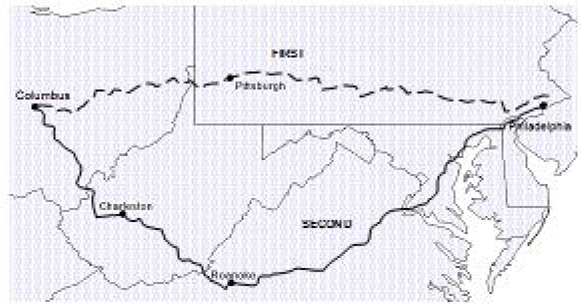


Fig. 2. Problem instance

section is used to analyze a problem instance involving rail transportation of hazmat from Philadelphia to Columbus. Figure 2 depicts the two distinct rail-routes recreated, along with the population zones, in ArcView GIS [15]. Each route has a set of tracks on which the train traverses, and a number of nodes (yards) it serves. The shorter of the two measures 647 miles and goes through Pittsburgh, while the longer labeled the second route is 814 miles. The objective is to determine the best way to move 10 hazmat railcars such that the transport risk is minimized. Note that this implies not just a decision about the route but also the placement of railcars in a train.

### *B. Parameter Estimation*

Train-accident rates were estimated using FRA website, and a value of 1.48 x $10^{-6}$ for mainline, and 17.13 x $10^{-6}$ for switching yards were obtained. Furthermore, based on the GIS map available at FRA website, the track type for the realistic problem instance is mainline with switching yards at the intermediate stations.

Conditional probabilities were estimated by applying logical diagrams and Bayes theorem to the dataset containing derailment statistics from 1995 to 2009, in two stages. In the first stage, a database was built by retrieving details on all freight-train derailments reported with the FRA from 1995 to July 2009. Each report was parsed to determine the number of regular and hazmat railcars, how many of each type derailed, the point-of-derailment (POD), and the number of hazmat railcars with release. Each parsed record was categorized into *short* (S), *medium* (M), and *long* (L) trains. In the second stage, each complete record was further processed, using logical diagrams and Bayes theorem, to calculate the required conditional probabilities.

For exposition reasons, we just produce the estimated values for *medium* trains, and note that the conference presentation will include estimations for the other two train lengths (table I). It can be concluded, that on average, the front-half of the train is riskier than the rear-half, and that the risk of derailment is the highest in the $1^{st}$decile. On the other hand, $7^{th}$decile appears to be safest if the train has less than 121 railcars, and $8^{th}$ for all other lengths.

Population exposure determination would require two pieces of information, viz. the number of hazmat railcars with release and the quantity released from each. While the FRA database was used to estimate the expected number of hazmat railcars with release, a significant number of entries had no




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TABLE I. CONDITIONAL PROBABILITIES FOR *MEDIUM* TRAINS

| Train *Decile* | $X = P(D^i \mid A_i)$ | $Y = P(H \mid X)$ | $P(R \mid Y)$ |
|---|---|---|---|
| *1st* | 0.1884 | 0.0417 | 0.0156 |
| *2nd* | 0.1001 | 0.0838 | 0.0141 |
| *3rd* | 0.0897 | 0.0746 | 0.0108 |
| *4th* | 0.0947 | 0.0803 | 0.0127 |
| *5th* | 0.0895 | 0.0792 | 0.0120 |
| *6th* | 0.0834 | 0.0761 | 0.0121 |
| *7th* | 0.0816 | 0.0718 | 0.0061 |
| *8th* | 0.0870 | 0.0776 | 0.0087 |
| *9th* | 0.0826 | 0.0579 | 0.0070 |
| *10th* | 0.1032 | 0.0883 | 0.0054 |

information on the quantity released, which necessitated using an approximate estimation technique. It has been shown in literature [12] that a rupture diameter of 4 inches or more will result in the loss of entire lading within 10 minutes, which is less than the anticipated response time for emergency response providers. In reality, response time will exhibit a lag of at least 10 minutes, and hence it is not unreasonable to assume total loss of lading from derailed railcars. Finally, in an effort to provide the most conservative estimate, we evaluate transport risk from each of the 10 hazmat railcars.

### C. Solution To The Problem Instance

The specified demand can be met by either dispatching a non-stop train from Philadelphia to Columbus, or a freight train that stops at intermediate yards. Note that any of the three train-types (i.e., *short*, *medium*, and *long*) can be used under both the options on the *first* and *second* routes. The non-stop train can be of two types: a hazmat unit-train that will carry just the ten railcars; and, a (unit) train that will carry the ten hazmat railcars plus regular freight. Clearly the train-type for the former will be *short*, while the latter can be of all the three types. Note that the mixed unit-train, as well as the ones with intermediate stops, presents a number of ways to position hazmat railcars, and we elaborate on this in the following paragraphs.

It may be clear from the preceding discussion that expected consequence of a hazmat railcar depends on a number of factors, including its position in the freight train. Railcars position in a train-consist is influenced by the operating characteristics of the railroad industry, where the basic goal is to minimize the number and/or complexity of switching movements within yards, as well as those associated with the transport, set-out, and pick-up of railcars while en route, which is achieved by building and operating trains consisting of blocks of railcars in yard order [9]. Deviations from this goal are made as necessary to accommodate the Department of Transportation (DOT) regulations.

For expositional purposes, we create legends for different make-up options. In addition, we introduce subscripts *i* and *j*, where *i*= {S, M, L} refers to the three train-types and *j* = {1, 2, 3,…., 10} will indicate the ten train-deciles. Under the non-stop unit train (*UT*) alternative, it is conceivable to have the following train make-up plans. For *short* trains with 40 railcars: a hazmat unit-train, $UT_H$; a train that will carry both regular and hazmat freight, and where hazmat railcars can be placed anywhere in the train consist, $UT_{S,D}$; and, combinations involving the use of at least three train-deciles to place the ten hazmat railcars, since DOT regulations stipulate 5 railcar buffer at either end of the train. It is important to note that 120 combinations (i.e., $^{10}C_3$) involving at least three train-deciles are possible, but we will highlight just the best one. For *medium* trains with 120 railcars: a mixed freight-train, $UT_{M,D}$; and eight different configurations where the ten hazmat railcars can be placed in the 2nd to the 9th train-deciles. Note that given the DOT regulations, the ten hazmat railcars cannot be completely contained in either the 1st or the 10th train-deciles, and hence those configurations are not considered. Finally, for *long* trains with 200 railcars: a mixed freight-train $UT_{L,D}$; and ten configurations involving placement of the ten hazmat railcars from the 1st to the 10th train-deciles.

On the other hand, freight trains with intermediate-stops (*IS*) would be formed of blocks of railcars in the order of the yards it has to serve. This implies that both hazmat and regular cargo would be grouped in a block, and hence the position of hazmat railcars can only by varied within the specific block. Assume that the train, of any type, is formed of ten blocks, $IS_{i,1}$, $IS_{i,2}$, $IS_{i,3}$, …, $IS_{i,10}$, corresponding to the train-deciles. Finally, it is presumed that railcars (blocks) loaded/unloaded at the intermediate yards are non-hazardous. For the non-stop option, transport risk for all train-types is lower for *first* route, which implies that the *second* route is not just longer but also riskier and hence will not be considered in subsequent analysis. Before continuing with the analysis we would like to note that population centers surrounding the least risky path would be subject to frequent exposure, while there is a zero chance of any incident on the *second* route.

Table II depicts the expected consequence as a result of various configurations using non-stop (unit) trains between the origin-destination yards. Once again, for exposition purposes, we just report the results for *medium* trains. As expected, expected consequence under $UT_{S,D}$ configuration exceeds that under $UT_H$ since the former endeavors to maximize separation distance between two consecutive hazmat railcars, which generally will require increased handling at the yards. Of the 120 possible combinations needed to accommodate the ten hazmat railcars in at least three train-deciles, the one involving placement of four hazmat railcars each in the 7th and 8th decile, and the remaining two in the 9th decile results in the lowest expected consequence, and also the lowest risk for *short* train-type. For the *medium* train-type, the $\boldsymbol{UT_{M,D}}$ configuration is riskier than that for short train-types. This can be explained by the fact that around 56% of total trains are of *medium* type, and hence the probability of finding hazmat railcars and the associated release probabilities for various deciles are higher than that for *short* train-type. In conclusion, 7th through the 9th train-deciles carry very similar risks and should be chosen to move hazmat railcars, irrespective of the train-type. Transport risk, under any make-up plan for any of the three train-types, with intermediate-stop is higher than the equivalent non-stop option (table III).




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TABLE II. TRANSPORT-RISK FOR NON-STOP *MEDIUM* TRAINS

| Makeup | First | Second |
|---|---|---|
| $UT_H$ | - | - |
| $UT_{4,D}$ | $1.30 \times 10^{-2}$ | $1.47 \times 10^{-2}$ |
| $UT_{4,1}$ | - | - |
| $UT_{4,2}$ | $1.30 \times 10^{-2}$ | $1.66 \times 10^{-2}$ |
| $UT_{4,3}$ | $7.96 \times 10^{-3}$ | $1.02 \times 10^{-2}$ |
| $UT_{4,4}$ | $1.06 \times 10^{-2}$ | $1.36 \times 10^{-2}$ |
| $UT_{4,5}$ | $9.37 \times 10^{-3}$ | $1.20 \times 10^{-2}$ |
| $UT_{4,6}$ | $8.46 \times 10^{-3}$ | $1.08 \times 10^{-2}$ |
| $UT_{4,7}$ | $3.93 \times 10^{-3}$ | $5.03 \times 10^{-3}$ |
| $UT_{4,8}$ | $6.47 \times 10^{-3}$ | $8.26 \times 10^{-3}$ |
| $UT_{4,9}$ | $3.69 \times 10^{-3}$ | $4.71 \times 10^{-3}$ |
| $UT_{4,10}$ | - | - |

TABLE III.TRANSPORT-RISK FOR *MEDIUM* TRAINS WITH INTERMEDIATE STOPS

| Makeup | First | Second |
|---|---|---|
| $IS_{4,1}$ | - | - |
| $IS_{4,2}$ | $1.31 \times 10^{-2}$ | $1.67 \times 10^{-2}$ |
| $IS_{4,3}$ | $7.97 \times 10^{-3}$ | $1.02 \times 10^{-2}$ |
| $IS_{4,4}$ | $1.06 \times 10^{-2}$ | $1.36 \times 10^{-2}$ |
| $IS_{4,5}$ | $9.45 \times 10^{-3}$ | $1.21 \times 10^{-2}$ |
| $IS_{4,6}$ | $8.47 \times 10^{-3}$ | $1.08 \times 10^{-2}$ |
| $IS_{4,7}$ | $3.94 \times 10^{-3}$ | $5.03 \times 10^{-3}$ |
| $IS_{4,8}$ | $6.48 \times 10^{-3}$ | $8.27 \times 10^{-3}$ |
| $IS_{4,9}$ | $3.72 \times 10^{-3}$ | $4.74 \times 10^{-3}$ |
| $IS_{4,10}$ | - | - |

This can be explained by the additional handling of freight-train at intermediate yards, which increases the chances of hazmat release. It is interesting that the safest place to carry hazmat railcars, for the three train-types, is consistent for both make-up alternatives, and that front of the train is riskier. This also implies that if the destination (or any other yards in the network) demands hazmat railcars from one of the intermediate yards, those railcars should be placed in the next safest (available) train-deciles.To sum up, we can conclude that non-stop option is better for moving hazmat railcars than the one involving intermediate handling. Given a unit-train with both hazmat and regular freight, and for specified train-length, one could potentially distribute the hazmat railcars strategically so that the number derailed in the event could be kept as low as possible, although this will require increased handling at the marshalling yards. It is important that such separation be implemented without splitting the shipment over two (or more) trains, which clearly is not desirable from both customer service and operational efficiency perspective. Generally speaking, $7^{th}$-$9^{th}$deciles are the safest slots for carrying hazmat railcars, irrespective of the train-length.

Furthermore it can be shown, using eqn. (7), that the aggregate concentrate curve is non-linear and concave. This implies that population exposure, and hence the expected consequence, will increase at a decreasing rate if the number of hazmat railcars on a single train is increased. Although such a scenario may be preferred by the railroad companies, the low probability –high consequence nature of the event makes it un-desirable from emergency responders' viewpoint. We would like to note that expected consequence is an underestimate of the potential risk, since the exposure numbers are being conditioned by different probabilities. To that end, evacuation and related emergency activities should be planned based on exposure numbers as they are closer to real-risk. Finally, if the freight-train is carrying blocks for other destinations, then subsequent hazmat railcars should be assigned to the next safest available train-decile for the given train-length.

## CONCLUSION

This paper presents a risk assessment methodology of railroad transportation of hazardous materials when train-lengths are specified. This work is distinct from earlier efforts in that it makes use of the accident causal factors in the development of a composite indicator, and then considers the sequence of events leading to hazmat release from multiple sources and the associated consequences. Around 25,000 derailment records (reported with the FRA) were analyzed to get insight into the nature of railroad accidents and also to aid the development of appropriate methodology. Bayes Theorem and Logical Diagrams were used to estimate conditional probabilities of release events.

The proposed risk assessment framework was used to solve a case example, based on realistic size railroad network in US, which was then analyzed to gain additional insights. It was noticed that transport risk is a function of train length, train-decile position of the hazmat railcar, and the number of intermediate handling. Analysis of the empirical dataset revealed that the front of the train is riskier, and that $7^{th}$-$9^{th}$ train-deciles are most appropriate for moving hazmat railcars for freight trains of any length. Furthermore, it was concluded that rail-track risk can be reduced by strategically distributing hazmat railcars in the train-consist, although this will require increased handling at the marshalling yard.Finally, though sending fewer but larger shipments may be preferable to railroad companies, this policy should only be practiced if the emergency response system has the necessary infrastructure to handle unforeseen adverse events.

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